Fermi National Accelerator Laboratory

Beauty Physics at the Ultrahigh Energies
of the ELOISATRON*

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February 1988

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ABSTRACT:

The potential for experimentally studying B physics at the proposed INFN 100 TeV ELOISATRON (Euroasiatic Long Intersecting Superconducting Accelerator Synchrotron) is compared with possibilities at 40 TeV at the Superconducting Super Collider. The effect of the increase in center of mass energy on the production and decay of B mesons has been investigated, particularly with respect to the accumulation of large samples of B hadron decays necessary for the detection of CP violating effects.

INTRODUCTION:

Ambitious plans have been advanced for the construction of a Euroasiatic machine, the ELOISATRON, which would have considerably higher energy (100 TeV) than the 40 TeV presently planned for the Superconducting Super Collider. This makes it interesting to evaluate the effect that such an increase in collider energy would have on the production and decay of beauty quark states. In particular, the possibilities for producing large samples of various B meson states with the objective of detecting and measuring CP violation in their exclusive decay modes may be significantly enhanced by the higher energy. While the CP violating effects in various exclusive decay modes are expected to be large[1,2,3], the small cross sections for b quark production at present accelerator energies make accumulation of a large statistical sample of any exclusive decay mode difficult.

The possibility of experimentally studying B physics at the SSC has been investigated in the Snowmass 84 and 86 meetings[4,5,6] and other forums[7]. In addition, the possibilities for doing such physics at Fermilab in the TeV II fixed target program[8] and at the TeV I collider[9] are just beginning to be evaluated. The experimental problems and the potential of producing, detecting and completely reconstructing large samples of exclusive B decays at TeV II, TeV I, the SSC, and at the ELOISATRON are quite different and should be compared in detail. The issue

of collider verses fixed target experimental configuration will not be addressed in detail in this paper although, as will be mentioned below, there are advantages and liabilities in both approaches. It is interesting, however, to note that the most energetic B's for any of the present or proposed future experimental configurations are being produced now in TeV II fixed target hadroproduction experiments (even in comparison to B's produced the 100 TeV ELOISATRON interactions!). Accordingly, the potential for doing this sort of physics in a fixed target environment with external beams at the energy of the ELOISATRON beams is an interesting subject for further study at another time. The purpose of this document is to investigate whether the ultrahigh energy of the ELOISATRON collider gives special advantages in comparison to the SSC.

There are obvious enhancements in the capability of doing this sort of physics that come with higher energy. These enhancements occur in several areas:

CROSS SECTIONS:

The ratio of the gluon fusion dominated $b\bar{b}$ cross section to the total cross section grows rapidly with $\sqrt{s}$ since the $b\bar{b}$ cross section grows rapidly with energy (see Fig. 1) while the total cross section remains relatively constant. The rate of increase of the cross section with energy shown in Fig. 1 is that predicted by PYTHIA[10] but the level of the cross sections have been adjusted to take into account the meager experimental data that is available on the hadroproduction of beauty. The absolute level of the TeV II cross section has been determined from the WA78 measurement[11] of the B production cross section in π^-U interactions at 320 GeV/c. This measurement results in a π^-N cross section of $4.5 \pm 1.5 \pm 1.5$ nb when an A^1 dependence of b production on atomic number is assumed. Since this π^- nucleon cross section agrees well with the first order calculations of E. Berger[12], we have used the ratio of $\pi^-N \rightarrow b\bar{b}$ at 320 GeV/c to $pN \rightarrow b\bar{b}$ cross sections 900 GeV/c as calculated by Berger to estimate a pN cross section of approximately 14 nb per nucleon at $\sqrt{s} \approx 40$ GeV. This is approximately one quarter of the cross section for $pN \rightarrow b\bar{b}$ predicted by PYTHIA.
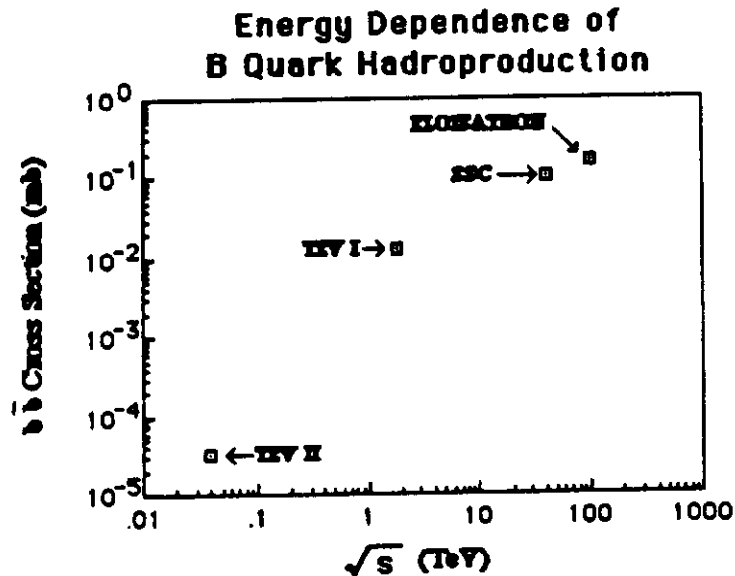

Figure 1: Growth of $b\bar{b}$ cross section in pp interactions as a function of $\sqrt{s}$.

The second piece of experimental evidence on $b\bar{b}$ production used to determine the absolute level of the cross sections of Fig. 1 is the $\sqrt{s} = 630$ GeV $pp \rightarrow$ high p_t dimuon data[13] of UA1. This data has been used to infer a $p\bar{p} \rightarrow b\bar{b}$ cross section of $1.2 \pm 0.1 \pm 0.2\,\mu b$ for the portion of the cross section at $p_t > 5$ GeV/c. Extrapolating to 1.8 TeV pp interactions by use of ratios of $p\bar{p}$ and pp cross sections obtained from PYTHIA, we obtain a $pp \rightarrow b\bar{b}$ total cross section of approximately 13 μb integrating over all p_t. This estimate is, once again, approximately one quarter of the 50 μb cross section estimated by PYTHIA. Therefore, we have decreased all cross sections calculated by PYTHIA by a factor of four but have retained the energy dependence for purposes of Fig. 1. If this energy dependence is valid we expect only 60% more cross section at the ELOISATRON that at the SSC.

Table I gives these cross sections and their ratios to total cross sections and indicates the relative richness of the higher energy collider interactions in $b\bar{b}$ production. The TeV II cross sections for Fig. 1 and Table I are calculated for an intermediate A target such as silicon.

Table I*

	TeV II	TeV II	SSC	ELOISATRON
$\sqrt{s}$ (TeV)	.040	1.8	40	100
$\sigma(b\bar{b})$ (cm^2)	$\approx 3 \times 10^{-32}$	$\approx 1.3 \times 10^{-29}$	$\approx 1.0 \times 10^{-28}$	$\approx 1.6 \times 10^{-28}$
$\sigma(b\bar{b})/\sigma_T(pN)$	$\approx 10^{-6}$	$\approx 10^{-4}$	$\approx 10^{-3}$	$\approx 1.6 \times 10^{-3}$
$\#b\bar{b}/10^7$ sec	$\approx 10^8$	$\approx 10^9$	$\approx 10^{11}$	$\approx 1.6 \times 10^{11}$

*The assumptions made in calculating the event rate for each machine is that the various detectors would be limited to 10^7 interactions per second, each experiment would run for 10^7 seconds of beam time and that the luminosity in the case of the TeV I collider would be 10^{31} cm^{-2} $sec-1$ (after upgrading).

The kinematic distributions of the b quarks produced in 100 TeV pp interactions (as predicted by PYTHIA) are shown in Fig. 2. The b quarks are produced at relatively low transverse momentum and with a relatively flat rapidity distribution.
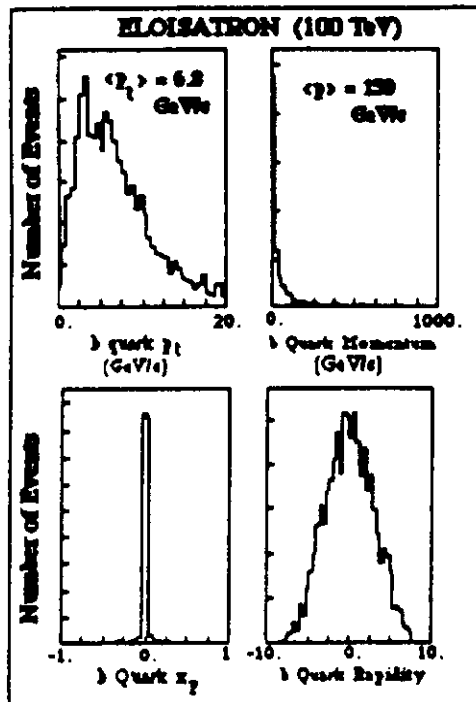

Figure 2: Production distributions of b quarks in p_t, momentum, x_F and rapidity in $\sqrt{s}$ =100 TeV interactions.

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PRODUCTION ANGULAR DISTRIBUTIONS OF THE BEAUTY QUARKS:

The dominant gluon fusion production mechanism for $b\bar{b}$ production, at the higher energies of the SSC and the ELOISATRON, leads to highly collimated $b\bar{b}$ events with both b and b both traveling along one or the other beam directions (see Fig. 3a). As has been pointed out[5,6], at the SSC, this collimation and correlation of the b and the $\bar{b}$ quarks makes possible the design of smaller solid angle spectrometers which are more heavily instrumented for precision spectroscopy with particle identification but which can still capture the decay products of b's a significant percentage of the time. The forward peaking of the b quark production increases approximately linearly with log(s) between the TeV I and the energy regime of the SSC and the ELOISATRON. This is shown in Fig. 3b for the TeV I, the SSC and the ELOISATRON collider configurations. The required solid angle coverage of a B spectrometer decreases both because of the increase in collimation and correlation with increasing s and because of the increase of the momentum of the b's in the forward direction with s discussed below.

MOMENTUM OF THE b QUARKS AND B HADRONS:

There is also a strong correlation of momentum of the b quark (and its corresponding B hadron) with laboratory angle (see Fig. 4a). The average momentum of b quarks in various angular regions is shown in Fig. 4b for TeV II, TeV I, the SSC and the ELOISATRON. Only in the most forward regions along either beam direction in the collider experiments does the momentum of the b's become appreciable while the central region on average contains only very low energy b's. The increase of s in the collider experiments causes an increase in the laboratory momentum of the b quark at all angles but the increase is most dramatic in the forward direction,
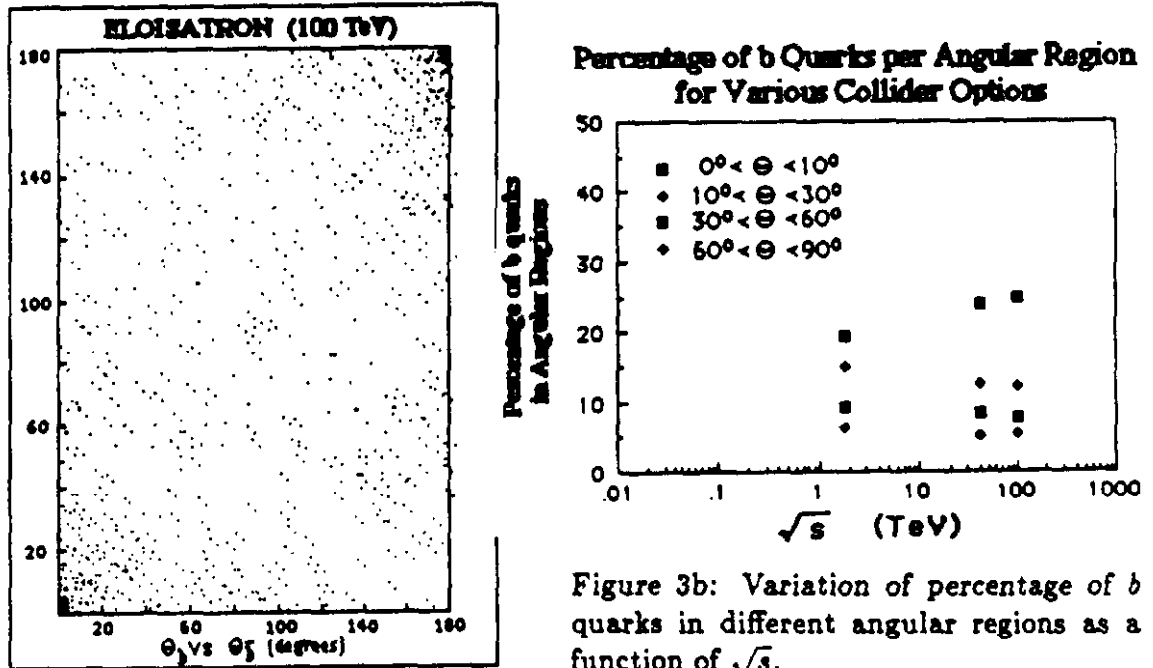

Figure 3a: Correlation of b and b quarks in laboratory angle at $\sqrt{s}$ =100 TeV.

Figure 3b: Variation of percentage of b quarks in different angular regions as a function of $\sqrt{s}$.

when the b quark and the resulting B hadron momenta are averaged over the entire solid angle, both averages appear to increase approximately linearly with $ln(\sqrt{s})$ for the collider configurations (see Fig. 4c). As noted above, the highest momentum b quarks and B hadrons for the four experimental configurations are already being produced in the Fermilab TeV II hadroproduction experiments. The increase in average momentum of B hadrons is considerably slower than increase in the average momentum of the b quarks due to the hadronization process leading to the b quarks. The b quarks are highly excited in the production process and must radiate gluons to return to the mass scale appropriate for hadronization into a physical B hadron. This gluon radiation, the level of which depends on the energy of the hard hadronic collisions, necessarily makes the resulting B hadrons considerably softer than the b quarks. Fig. 4c also indicates that the difference between the laboratory energy of the b quark and the B hadron is greatest for the TeV II experiments. While this is not fully understood, it may well to do with the combination of broadening of angular distributions in the hadronization process as well as the loss of energy in the hadronization of the b quark, both of which enter into the Lorentz transformation necessary to obtain the laboratory momentum of TeV II B hadrons.
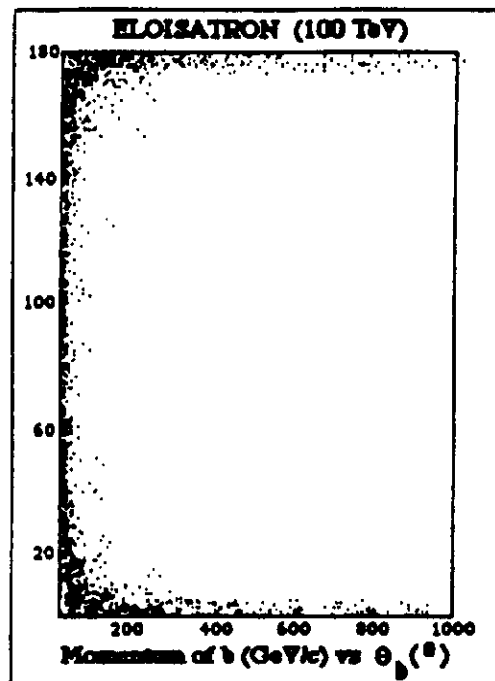

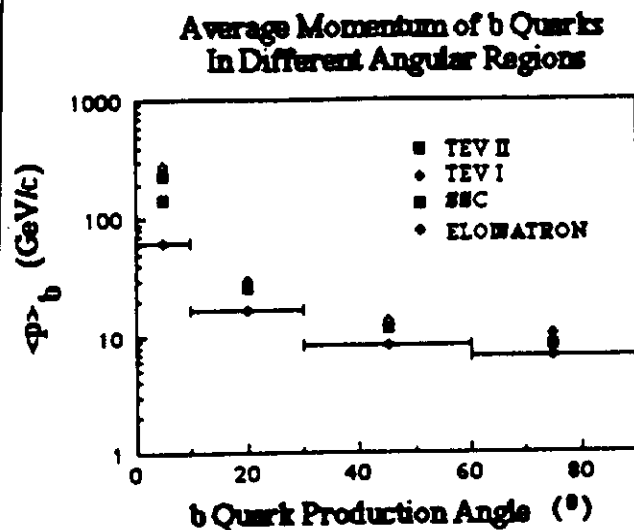Figure 4a: Correlation of momentum with laboratory angle in 100 TeV interactions.

Figure 4b: Average b quark momentum as a function of angle of b quark production for TeV II, TeV I, the SSC, and the ELOISATRON.
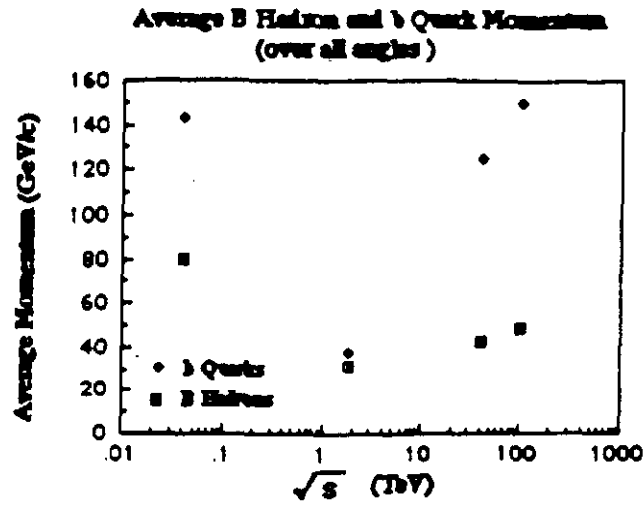
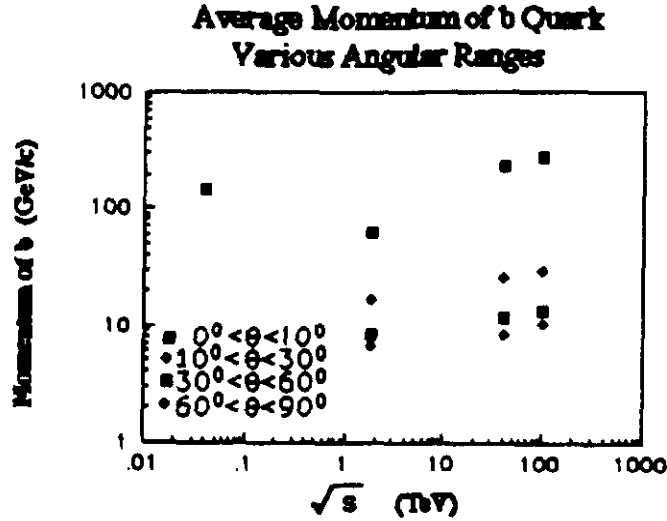Figure 4c: Average b quark and B hadron momentum as a function of $\sqrt{s}$

Figure 4d: Variation of Average b quark momentum with $\sqrt{s}$ for various laboratory angular regions.

The momenta of the B hadrons and their decay products is critical for triggering on and reconstruction of the B's. While it is true that an impact parameter calculated for a B decay is invariant with B momentum since

Δ = impact parameter $\approx$ decay length × laboratory decay angle of B decay product

$$= \{\gamma\beta c\tau\} \{(1/\gamma) \ \tan{(\theta*/2)}\} \approx c\tau \ \tan{(\theta*/2)}$$

is independent of γ, the multiple scattering of the decay products of the B's inversely proportional to the momentum of the decay products. The resolution on the impact parameter is degraded for low momentum decay products passing through microvertex measurement stations.

In addition, the higher the momentum of the decay products of the B's the easier triggering on those b's becomes. In reference 6 the problems of triggering on the muon pair from the psi decay of the B's was discussed. There the challenge is to prepare a thick enough muon detector to range out hadrons and muons from decays of K's and π's produced in total cross section interaction while avoiding ranging

muons from the B decay. The choice of thickness of the shield is a delicate balance between elimination of these trigger backgrounds and the retention of signal. The higher the momentum of the B's the more easily they are distinguished from the trigger backgrounds.

To illustrate the problem in achieving this separation the semileptonic decays of $B \rightarrow De\nu$ have been examined. In Fig. 5a the momentum distribution of the electron from this decay is plotted for the ELOISATRON. The average momenta of electrons from semileptonic decays in the four experimental configurations is shown in Fig. 5b. As indicated, the average momentum is 19.9 GeV/c at the ELOISATRON but this is deceptive. The distribution shows a long tail which skews the average much higher than it would be otherwise. More indicative is the
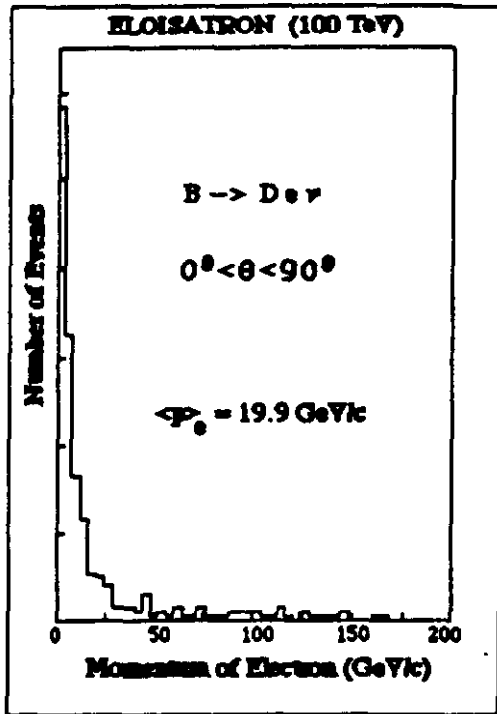

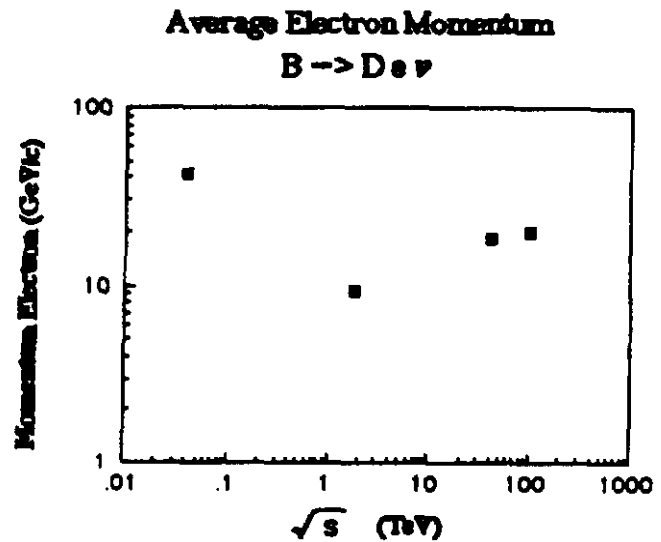Figure 5a: Momentum of the electron from the semileptonic decay, $B \rightarrow De\nu$ in 100 TeV interactions.

Figure 5b: Average electron momentum from the semileptonic decay, $B \rightarrow De\nu$ as a function of $\sqrt{s}$.

percentage of the electrons from this decay that are less than 4 GeV/c. As shown in Fig. 5c, the fraction of the flux with momentum less than 4 GeV/c decreases slowly with $ln(\sqrt{s})$ from approximately 70% at TeV I to slightly greater than 30% at ELOISATRON energies. By contrast, the electrons from the semileptonic decays at TeV II are much more energetic with less than 10% having momenta less than 4 GeV/c.
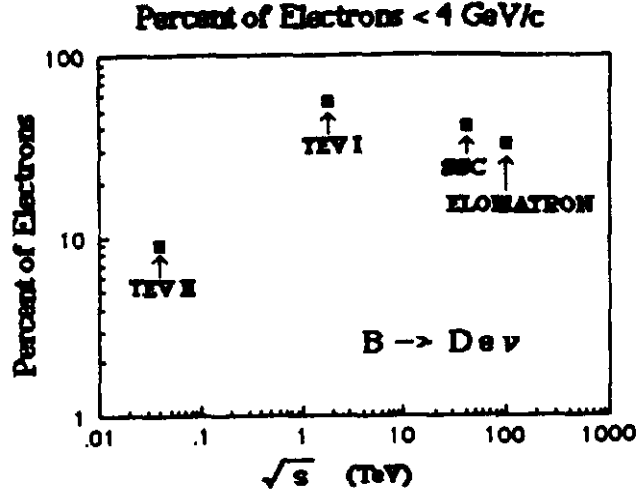
Figure 5c: Percentage of electrons from the semileptonic decay, $B \rightarrow$ Deν with momentum less than 4 GeV/c as a function of $\sqrt{s}$.
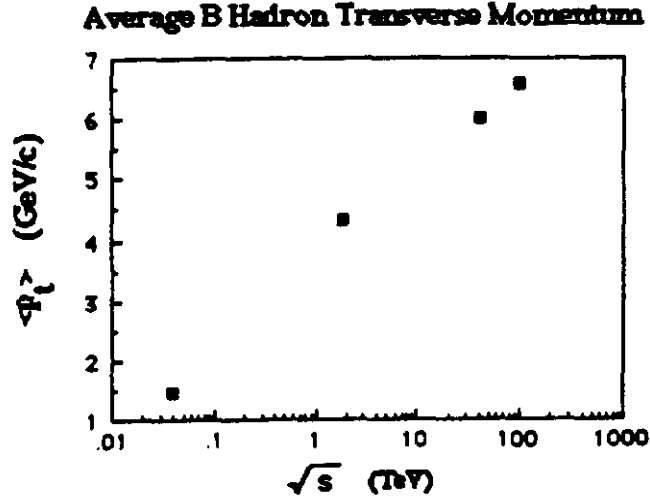

Figure 6: Growth of average B hadron transverse momentum with $\sqrt{s}$.

On the other hand, if we examine the average transverse momenta of the B hadrons as a function of $\sqrt{s}$, an advantage of the higher energy collider interactions becomes obvious. As shown in Fig. 6 the average transverse momentum increases linearly with $\ln(\sqrt{s})$ from about 1.8 GeV/c at TeV II to 6.7 GeV/c at the ELOISATRON. This increase in the transverse momentum of the B's is mirrored in an increased separation of the primary and secondary vertices in the plane transverse to the beam direction. This is the plane in which the greatest resolution in the reconstruction of the secondary vertex position is obtained using the planar silicon detector configurations that the forward collimation of the B production makes possible. The separation of primary and secondary vertices at the ELOISATRON are shown in Fig. 7a assuming a B lifetime of 1.2×10^{-12} seconds and the given choice of mixing and CP violation parameters. The separation in the transverse

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plane shown in Fig. 7b averages approximately 178 microns, much larger than the expected resolution for reconstruction of the transverse separation of primary and secondary decay vertices. The primary decay vertex is constrained to be within the interaction region which will be of order 10 microns in radius for high energy machines like the SSC or the ELOISATRON. So the measurement error will come mainly from the determination of the secondary decay vertex and should be of order of a few tens of microns.
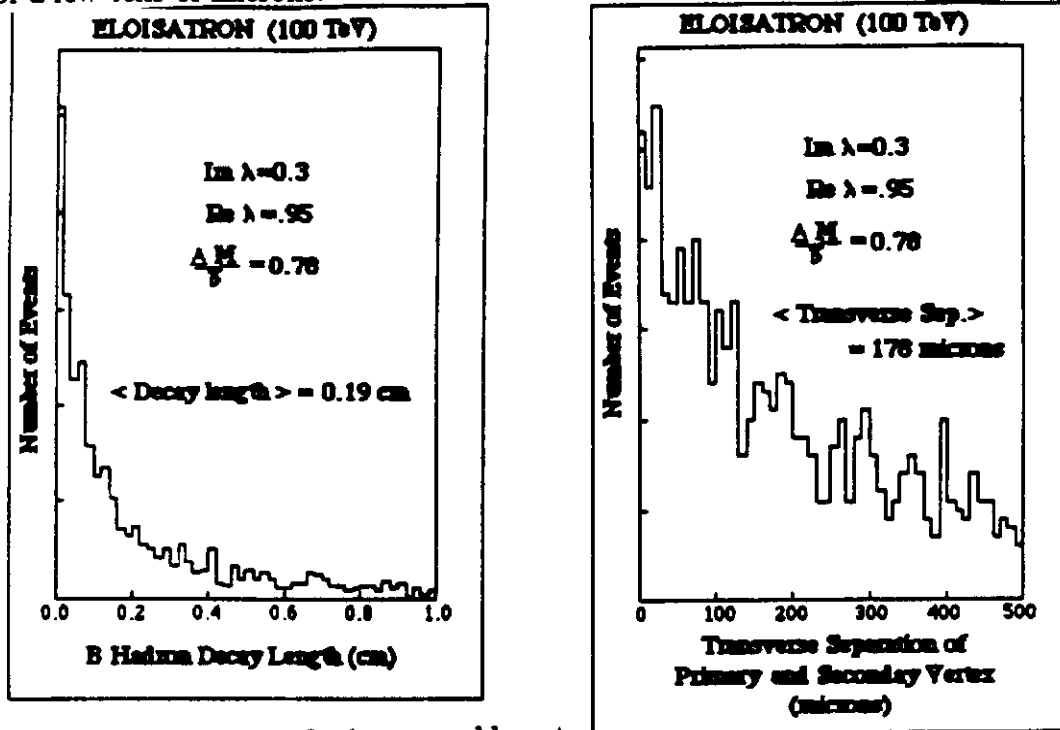

Figure 7a: Separation of primary and beauty hadron secondary vertices in 100 TeV pp interactions.

Figure 7b: Separation of primary and beauty secondary vertices in the plane transverse to the beam direction.

CONCLUSION:

There are several advantages of the ELOISATRON relative to the SSC for collider type B experiments (larger cross sections, larger average momenta, and larger average transverse momenta plus more collimation and correlation of the $\bar{b}$ and b). However, these improvements are not large and would not seem to be crucial unless the final strategies for obtaining evidence for CP violation are marginal statistically. Since this may well be the case (see the Snowmass 86 references), more study of the ELOISATRON possibility is merited. Perhaps even more interesting may be the potential for B physics with fixed target beams at the ELOISATRON since the fixed target configuration has some experimental advantages. The possibilities of both the ELOISATRON collider and fixed target options for doing B physics should be investigated further as the machine parameters become better established.

ACKNOWLEDGEMENTS:

thank those associated with the ELOISATRON workshop and especially the director, Ahmed Ali for their hospitality and the opportunity to investigate the issues addressed in this paper.

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